

ENHANCED DAMAGE-RESISTANT OPTICS

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DAMAGE-RESISTANT OPTICS FOR
SPACEFLIGHT LASER SYSTEMS: WORKSHOP
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FOR SPACEFLIGHT LASER SYSTEMS

Workshop Findings and Recommendations

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EXECUTIVE SUMMARY

On September 10–12, 1991, the NASA Office of Safety and Mission Quality (OSMQ), Technical Standards Division, sponsored a workshop in Newport News, Virginia, to address optical damage problems associated with NASA's current and future use of laser systems for space-based remote sensing. In response to the Global Change Initiative, NASA has begun several laser remote sensing programs designed to monitor major Earth variables such as aerosols, atmospheric constituents, and greenhouse gases. These missions are scheduled for launch as early as 1992 and will continue into the early 21st century. The success of these missions depends on the reliable operation of the laser systems throughout the mission duration.

A critical factor limiting the reliability of these systems is physical damage to the optical components caused by interaction of the intense laser energy with imperfections and impurities embedded in the materials. Although this damage can occur instantaneously upon exposure to the laser beam, catastrophic damage is often the result of cumulative exposure over time. As the majority of NASA's remote sensing missions require a duration of 5 years or more, optical components in these systems will be required to withstand 10^7 – 10^9 pulses during the course of an experiment. The result of such exposure levels on optical components has not been addressed by the laser community, and the reliability of the laser systems is dependent on the determination of these effects.

Ongoing NASA programs, including the Lidar In-Space Technology Experiment (LITE) and the Lidar Atmospheric Sensing Experiment (LASE), have experienced schedule delays and budgetary problems as a result of laser-induced damage to optical components. Other government and industry laboratories have had similar experiences with laser-induced damage. They have resolved their problems through concentrated efforts in manufacturing technology, certification testing, and standards development. However, these results are generally inapplicable to NASA systems because of the different operating conditions. The wide range of wavelengths, pulse lengths, exposure durations, and operating environments required by NASA flight programs are unique and are typically not of interest to the remaining laser community.

In response to this problem, NASA has defined a program to address critical laser-induced damage issues peculiar to its remote sensing systems. The Langley Research Center (LaRC), with input from the Goddard Space Flight Center (GSFC), has developed a program plan focusing on the certification of optical materials for spaceflight applications and the development of techniques to determine the reliability of such materials under extended laser exposures. This plan involves cooperative efforts between NASA and optics manufacturers to quantify the performance of optical materials for NASA systems and to ensure NASA's continued application of the highest quality optics possible for enhanced system reliability.

A review panel was organized to assess NASA's optical damage concerns and to evaluate the effectiveness of the LaRC proposed program plan. This panel consisted of experts in the areas of laser-induced damage, optical coating manufacture, and the design and development of laser systems for space. The panel was presented information on NASA's current and planned laser remote sensing programs, laser-induced damage problems already encountered in NASA systems, and the proposed program plan to address these issues. Additionally, technical presentations were made on the state of the art in damage mechanisms, optical materials testing, and issues of coating manufacture germane to laser damage.

Based on the information presented during the course of the workshop, the panel concluded that NASA's unique laser requirements demand the establishment of a specific NASA program to address optical component reliability. Provided with unlimited resources, a comprehensive laser reliability and assurance program could be put into place. Considering the realistic funding constraints (i.e., annual program support on the order of \$500,000), the panel endorsed a more focused program, concentrating on the testing and certification of optics for those spaceflight programs currently under development. The panel stressed initiation of this effort as soon as possible to ensure that results can be applied effectively to system design and development. The specific panel recommendations are summarized as follows:

NASA should establish a program to develop damage tolerant laser systems meeting NASA specific parameters for reliable operation in the space environment for long lifetimes. This program should be the central NASA laser-damage activity charged with coordinating NASA intergovernment laser-damage efforts, as well as related systems engineering and information transfer efforts among pertinent NASA flight programs.

Time is of the essence. The program should commence in FY 1992 in order to produce results by 1995. To succeed, the program must make maximum possible use of the existing laser-optics development, production, and characterization expertise in industry, Department of Defense (DOD), Department of Energy (DOE), and university research communities.

Test facilities and testing standards must be established from which certification procedures can be derived for NASA use in qualifying optical components for flight-platform use. Special emphasis must be placed on the development of test protocols for estimating the lifetime durability of optical materials. All documentation related to such standards should be compiled into a general-use NASA Handbook on Optical Components for Laser Systems.

Several technical activities need to be pursued in concert with this program to ensure reliability for NASA's laser remote sensing missions. Longer term program support must be maintained at an adequate rate, and efforts in related issues, such as damage mechanisms in materials, must be addressed, although these may be outside the scope of this effort.

In summary, the panel recommended the timely start of the proposed program for ensuring reliability of NASA laser remote sensing missions. However, the panel suggested that the NASA program specifically address testing, standards development, and qualification of components for NASA's programs. Additional efforts in damage mechanism determination and manufacturing improvements should be performed in concert to ensure overall reliability of optical materials.

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INTRODUCTION

Perhaps the most valuable return from the U.S. space program will reside in the understanding of the Earth, particularly as an operational system. This would be a near-term, "at-home" payoff in contrast with the typically envisioned missions to the Moon and far outer limits of the solar system. Near-Earth is, clearly, the regime where NASA has the greatest potential to benefit citizens, not only of this country, but of the world.

A known (but largely undefined) relationship currently exists between man and the environment in which detrimental changes can occur. However, positive changes can be implemented. Change usually is accomplished at the economic expense of man. This makes the precise definition and determination of cause-effect-impact an international goal. Thus, it is the duty of the industrial nations to investigate these relationships to preserve the human species, and ultimately, countless other species.

What are the atmospheric parameters in which we entrust our critical environmental knowledge—knowledge necessary to maintain a balance between environmental preservation and economic prosperity? Clearly, chemical reactions with the upper ozone layer and the chemical

transport phenomena thereof are among the foremost parameters over a relatively near-term period of interest. On the other hand, interest in the long term (where reversibility sometimes can be more difficult or impossible to implement) is exemplified by global warming concerns (i.e., different chemicals such as carbon dioxide are involved). Likewise, long term and short term rain precipitation forecasts and weather forecasting are important. Acid rain sources and their transport comprise other environmental concerns.

Understanding the science of these critical phenomena means we must acquire a tremendous three-dimensional environmental database that establishes technical requirements for NASA's earth science missions. These data requirements include high vertical resolution profiles, as well as global coverage that dictates the use of laser, active remote sensing systems for future NASA missions. We gain an appreciation of the diverse nature of NASA's physical parametric requirements from Tables 1a and 1b and the large variety of lasers necessary to measure the environmental parameters from Table 2.

TABLE 1a. Observation Requirements: Global Atmospheric Chemistry Cycle

OBSERVATION	SCIENCE PROBLEM	MEASUREMENT CHARACTERISTICS
CO ₂ , CO, CH ₄	Understanding biogeochemical cycles	3 weighting functions in troposphere 0-15 km, 10 km horizontal resolution, CO ₂ resolution \pm 0.3 ppmv, CO resolution 10 ppbv to 0.3 ppmv, CH ₄ from 100 ppbv to 3 ppmv
OH	Tropospheric lifetimes of atmospheric chemicals such as CO, CH ₄	0.5×10^6 molecules/cm ³ lowest deductibility
NO ₂ , NO, NH ₃ , N ₂ O	Nitrogen cycle	0.1 ppbv lowest deductibility
HNO ₃ , NO ₃	Nitrogen cycle	0.05 ppbv lowest deductibility
SO ₂ , H ₂ S, COS and other sulfur compounds	Sulfur cycle	0.05 ppbv lowest deductibility
H ₂ , H ₂ O	H cycle	H ₂ to 0.02 ppmv, H ₂ O from 1 ppmv to 5×10^3 ppmv
O ₃	Oxygen and oxidant cycle	O ₃ from 2 ppbv to 2000 ppbv
Aerosols	Aerosol cycle (including sulfur cycle and nitrogen cycle)	From 0.1 $\mu\text{g}/\text{m}^3$ to 100 $\mu\text{g}/\text{m}^3$
Temperature, wind velocity, clouds, rainfall rate, lightning	For interpreting all cycles	1 km vertical resolution, wind to 1 m/s ⁻¹

From "Earth Observing System Appendix Volume I, Part II Working Group Report." NASA TM-86129, August 1984.

TABLE 1b. Observation Requirements: Middle Atmosphere Science

OBSERVATION	SCIENCE PROBLEM	MEASUREMENT CHARACTERISTICS
Atmospheric Temperature	Chemistry, Dynamics, Transports, Energetics	Surface—150 km Resolution ~ 1/2 scale ht. Accuracy $\leq \pm 2^\circ\text{K}$ 0-80 km $\leq \pm 5^\circ\text{K}$ 80-120 km $\leq \pm 10^\circ\text{K}$ 120-150 km Precision 1/2 of Accuracy
Winds	Dynamics, Transports	Surface \rightarrow 50 km, $\pm 20^\circ$ LAT \pm 3 m/s $>$ 50 km, - 150 \pm 10 m/s
Constituent Concentrations Source Molecules O ₃ , N ₂ O, CH ₄ , CFCl ₃ , CF ₂ Cl ₂ , H ₂ O Reservoir Molecules HCl, HNO ₃ , H ₂ O ₂ , HNO ₄ , ClONO ₂ Radicals ClO, NO, NO ₂ , OH, HO ₂	Chemistry, Transports	Various Altitudes ~ 10% Accuracy Necessary ~ 5% Desirable Precision ~ 1/2 Accuracy 1/2 scale height vertical resolution
Emission Features O ² (¹ Δg), OH Bands 1-4 μm NO (2.9 μm, 5.3 μm) CO ₂ (4.3 μm, 10.4 μm)	Energetics of Upper Mesosphere—Lower Thermosphere (NON-LTE Excitation)	1/2 scale height vertical resolution, Spatial Distribution Desirable Accuracy ~ 25% Precision ~ 10%

From "Earth Observing System Appendix Volume I, Part II Working Group Report." NASA TM-86129, August 1984.

TABLE 2. Solid State Lasers Required for Near-Term Environmental Science Missions

Environmental Parameter	Laser	Wavelength (μm)	Pulse Length (ns)	Repetition Rate (pulse/sec)	Lifetime (pulses)
Aerosol	Nd: YAG	1.064	20	10	10^7 - 10^9
	2X	0.532	20	10	
	3X	0.355	20	10	
Water Vapor	Nd: YAG	1.064	~ 25	10	10^7 - 10^9
	2X	0.532	~ 20	10	
	Ti: Al_2O_3	0.815	~ 25	10	
Wind	CO_2	9.28	3000	10	10^7 - 10^9
	Ho:Tm:YLF	2.06	600	10	
Geology	Nd:YAG	1.064	0.075	40	10^7 - 10^9
	2X	0.532	0.075	40	
	3X	0.355	0.075	40	

Acquisition of the data, which will enable us to understand and model Earth's total environmental system, will require active sensors located primarily in spacecraft. The enormous volume of data on a global scale means that aircraft coverage is not possible. Thus, spacecraft sensors will probably supplant aircraft as the principal measurement platform.

Further, active sensors must be used rather than passive ones. Active sensors using lasers will enable the resolution of atmospheric constituents in space and time, whereas this cannot be adequately done with passive sensors. For example, a pulsed laser radar (lidar) can provide high vertical resolution ozone concentration profiles (100 m resolution, limited only by laser pulse length), a great improvement over obtaining just the average column content or concentration with nonlaser techniques (> 1 km resolution). As another example, lidars enable detailed measurements of atmospheric wind. By using heterodyne detection, radial wind velocity can be determined by measuring the degree of Doppler frequency shift of the return signal.

This change from aircraft to spacecraft and passive sensors to laser sensors makes mandatory, however, major improvements in the reliability of the laser sensors since (a) they will be inaccessible for maintenance in space, and (b) they must operate over a sufficiently long time to make the data acquisition cost effective because of the high cost of a spacecraft mission. Therefore, laser system lifetimes must be extended to, say, 5 years at a minimum, translating into 1.6 billion pulses for a laser operating night and day at a 10 pulse-per-second repetition rate. A failure in an aircraft means that the flight is aborted, and the instrument is repaired and reflown. But in space, the cost of a mission loss can be the termination of a very expensive spacecraft plus the waste of considerable launch costs.

To achieve the payoffs of active lidar sensors in spacecraft, NASA will need to seriously address the one major problem limiting laser lifetime: laser-induced damage to optical surfaces and their coatings that are in the path of the transmitted laser beam. Peak energy density, the key laser parameter that causes damage, is the principal design constraint in making lasers smaller, lighter, and less expensive.

Although industry can make lasers possessing lifetimes measured in months or hundreds of thousands of pulses, there is no experience base in making lasers with the reliability needed by NASA (unattended for years; 10^9 pulses), even if one tried to achieve it by derating the laser system. It is highly unlikely, therefore, that these requirements will be addressed by any other government agency or industry.

As a result, OSMQ requested NASA Langley Research Center (LaRC) to outline a program plan addressing reliability issues affecting space based laser sensors and to convene a workshop staffed with a panel of experts to advise on it. The workshop was held at the Omni Hotel in Newport News, Virginia, on September 10-12, 1991. The panelists consisted primarily of experimentalists who individually have many years of experience in the laser damage field, including test methodology, optical coating design, laser-induced damage mechanisms, and NASA laser system development. The panel's charter was to review the proposed program and provide comments on its appropriateness for impacting the reliability of NASA's laser sensor programs.

LASER-INDUCED DAMAGE AND ITS IMPLICATIONS TO NASA

The principal design constraint in high power laser systems stems from laser-induced damage to optical components in the path of the laser beam. This damage may be catastrophic (i.e., permanent) or transient in nature and can be considered as any alteration in an optical element makes it unable to perform its intended function within stated limits. These changes can affect the laser system's efficiency, lifetime, and maintenance requirements, and ultimately its reliability.

Optical damage spans the range from microscopic changes, which are only observable by evaluation with some microscope, to macroscopic damage, which is observable by the unaided eye or with a simple, hand-held magnifier. As microscopic mapping of optical surfaces is an inherently time- and manpower-consuming activity, more often than not, only macroscopic damage is monitored by laser operators. However, comprehensive damage studies have shown that, especially in high average output-power systems, macroscopic damage is preceded by some microscopic changes as well. Nevertheless, as long as macroscopic damage has not set in and output performance is not alerting the operators, these ground-based laser systems remain in use. This practice indicates that NASA's space-based laser systems may be reliably operated with some degree of optical damage, as long as the laser's output is not degraded.

Laser-induced damage can be either intrinsic or extrinsic in origin. Intrinsic damage is a component-specific failure mode, resulting from the absorption of laser energy by impurities or defect sites in the optical material. Liberated heat, and/or vapor products, in the small volume of the defect, generate localized fracture or melting of the material. These impurities are typically incurred during manufacturing processes, including crystal growth or glass melting (e.g., impurities desorbed from the crucible walls or dopant gradients across a crystal boule), substrate polishing (e.g., imbedded polishing residues), or coating deposition (e.g., structural defects or nonstoichiometry).

Extrinsic damage mechanisms are the result of operation of the component in a system. Possible extrinsic failure modes of interest to NASA's systems include the adsorption of linear or nonlinear materials into porous coatings from outgassing of soldering resins, printed circuit (PC) boards, and wire insulation, or the adsorption of water vapor into materials prior to launch due to storage in a humid environment. Similarly, uncontrolled events, such as particles floating through the beam path during operation or the deposition of ceramic, glass, metallic, or polymeric material on an optical surface, will cause unforeseen, high-intensity diffraction that promotes local damage.

In addition, a tendency exists among system designers to accept high-risk oscillator and beam-transport designs, especially when every last millijoule of output energy must be extracted from every gram of gain medium. Such designs are difficult to control in terms of their intensity near-fields and, more dangerously, in terms of their temporal pulse instabilities. Designs that are prone to spontaneously modelock (i.e., deliver very short, high intensity spikes) are inherently dangerous to even the best of coatings and materials. Testing for optical damage requires well-characterized laser sources, as well as an adequate damage detection system. A schematic of a typical damage test station is provided in Figure 1. The laser beam is focused to provide for several irradiations per optic, and damage is typically monitored both by on-line scatter changes and post-test microscopic evaluation. By varying the energy density or power density of the beam, a probability of damage versus fluence graph can be generated as shown in Figure 2.

Existing Reference Material on Optical Damage

The phenomenon of laser-induced damage has been the subject of significant theoretical and experimental research since the beginning of laser technology. The most comprehensive accounts

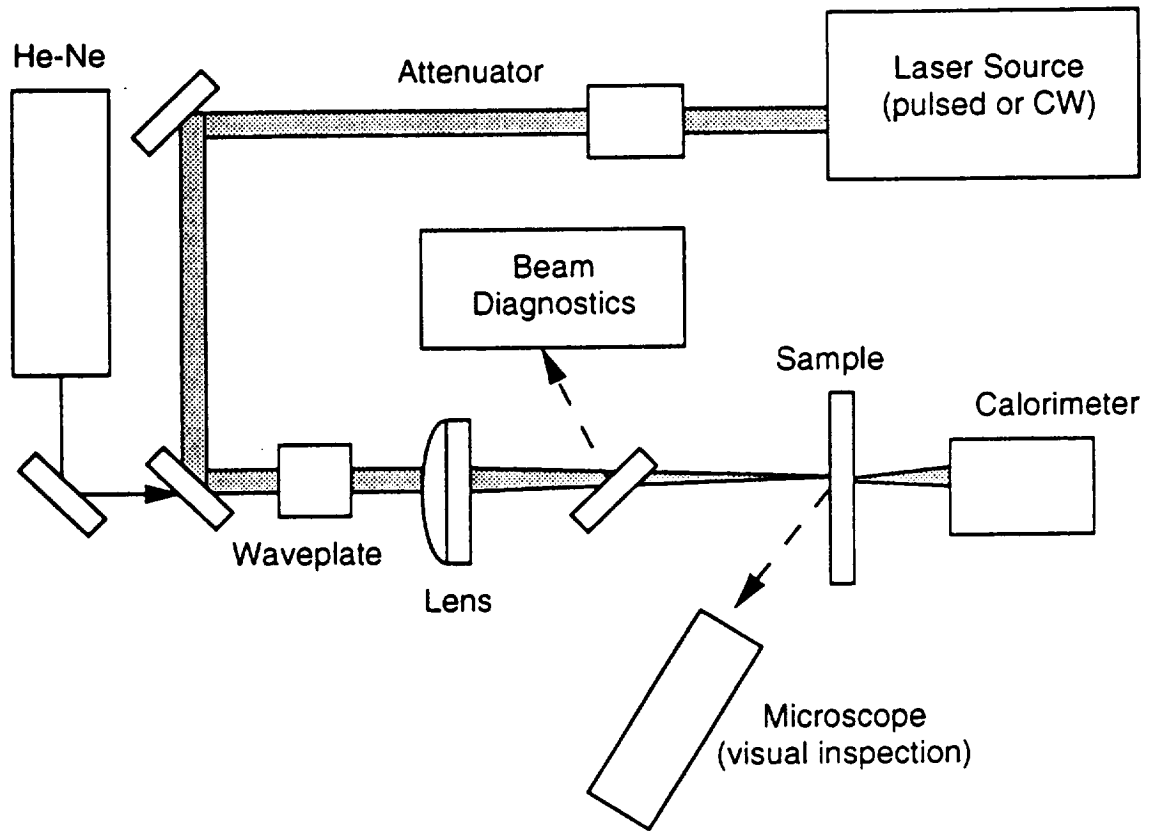


Figure 1. Schematic of typical damage test station.

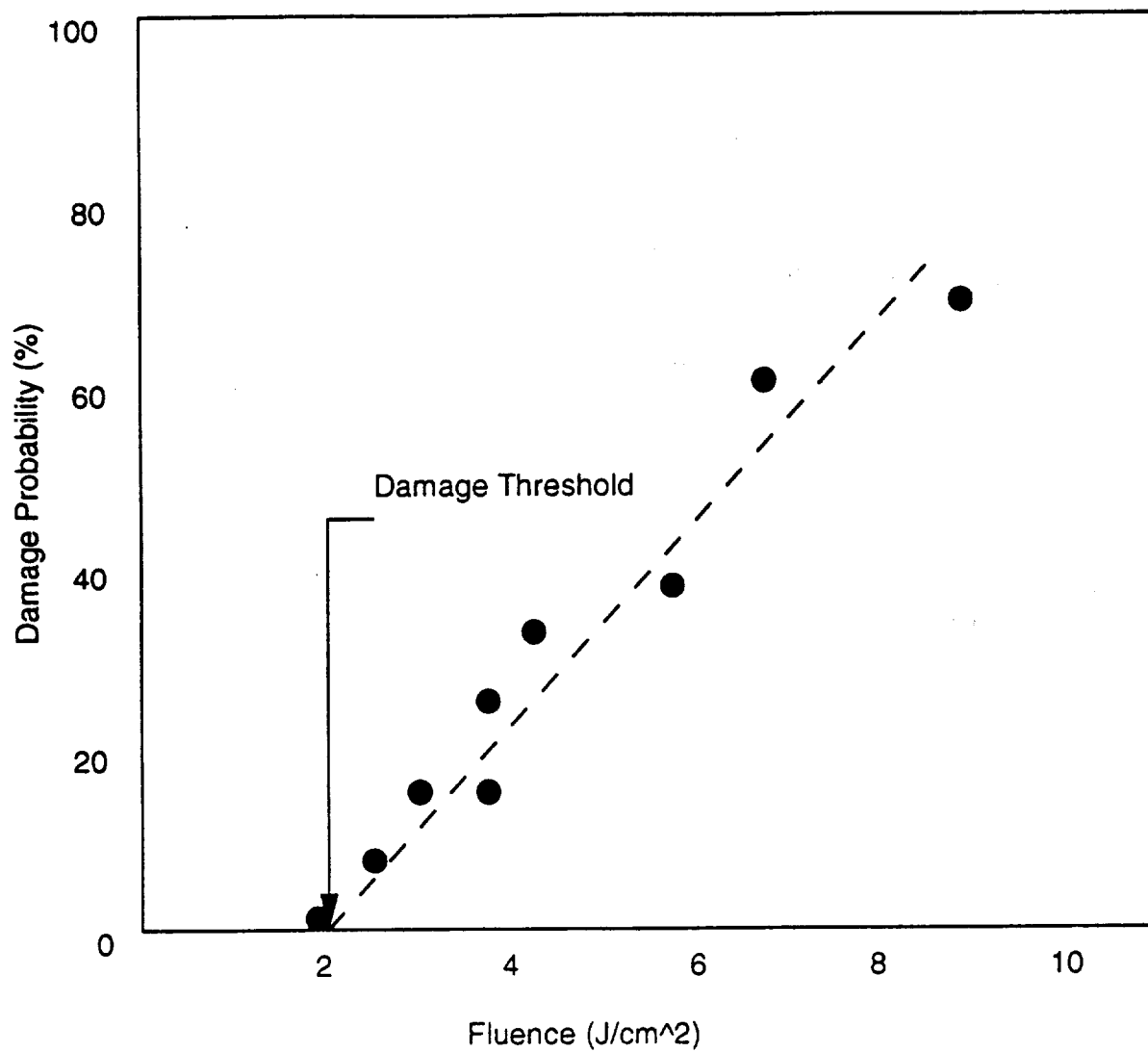


Figure 2. Probability of damage versus fluence plot.

of this research are the proceedings volumes of the annual Boulder High Power Laser Materials Conference, which has been conducted since 1969. Additionally, the testing capability at Montana Laser Optics Inc. (MLO) has generated an extensive database at 1064 and 532 nm for selected component materials.

Unfortunately, much of the older information on optical damage is not only dated, but also limited in its usefulness, as critical coating and material characterization information on early samples is missing. This shortcoming is further compounded by missing information on how reported results track from coating run to coating run or after scaling of specimens to larger diameters. The time is ready for separating out of this data the valuable portion and sorting it into a modern medium that all NASA programs, as well as the optical materials community, can access.

Optical Materials Development

As previously mentioned, the vast majority of laser-damage events result from laser energy transfer to localized absorbers embedded in the coating or substrate material. Improving the reliability of optical components against laser damage, therefore, is first and foremost an impurity elimination task. This task requires improvements in the purity of raw materials, materials processing, and specimen characterization.

Most oxides and fluorides used in optical material fabrication have, over the past twenty years, experienced progress in purification at acceptable costs. Further improvements in this area, therefore, will come at a steeper cost and at increased uncertainty about enhanced optics reliability. Investment in improvements in materials processing and characterization will offer more chance for increased durability and reliability.

Recent dramatic improvements in the laser damage thresholds of optical materials can be credited mostly to improvements in materials processing and handling. Advancements in semiconductor fabrication through refined crystal growth, use of cleaner processing environments, and improved film deposition techniques have also affected the preparation and processing of more damage resistant optical materials.

However, one of the key challenges at this time revolves around the lack of reproducibility in preparing exemplary optical coatings. While the literature reports the development of several high damage threshold coatings, repeatability of these coatings from run to run has not proven successful. It is to NASA's advantage that, on each mission, only a limited number of components are required, which somewhat minimizes the need for the exact reproducibility typically demanded under mass production conditions. However, because of NASA's extreme reliability requirements, the challenges of making just a few, exceptional coatings may equal any effort to reproducibly coat a less demanding type of optic in larger numbers.

One challenge to coating production lies in film growth anomalies, referred to as nodules, that typically result from the far-from-thermal-equilibrium, vacuum evaporation process. Nodules and their boundaries are often directly or indirectly linked to laser damage. Development of deposition processes that minimize nodule density is pivotal to raising film damage thresholds. Significant strides have been made in enhancing the damage resistance of conventionally deposited coatings by supplemental treatments of the film lattice structures, including such techniques as ion-assisted deposition, post-deposition bake routines, and ion plating. Other deposition techniques, that produce bulk-like thin films possessing higher damage thresholds, such as molecular beam epitaxy, have also been investigated but have not been used on a large scale because of the high capital investment and lower yields. These techniques may deserve to be reconsidered for applications requiring a few, exceptional coatings.

Another promising, but largely unexplored area of coating improvement is the use of hybrid processing, in which conventional, porous dielectric coatings are protected against infiltration by environmental agents by a low permeation organic membrane deposited as a coating top layer. This mixing of organic chemistry methods with conventional, inorganic materials research has parallels in other optical materials areas, including sol-gel glass preparation, doped and undoped fibers, and integrated optics frequency conversion structures. Applied to thin films, hybrid processing requires relatively modest capital investments and promises high payoff. What is, however, currently entirely unknown is the space compatibility of such polymers, their affinity for atomic oxygen, and their radiation hardness.

Finally, perhaps the most important area of optics manufacture is detailed comprehensive materials characterization. Optical materials preparation, much like any other materials research, is a complex multiparameter process. Success in improving the results of this process critically depends on a detailed understanding of each parameter and its control. NASA's goal of improving optical component reliability will be reached only if the supplier of the material or coating is adequately equipped to analyze and document the various fabrication parameters. A proactive damage testing program must incorporate comprehensive characterization activities in conjunction with laser damage measurements. The challenge in organizing such a program is that few commercial vendors are equipped with adequate characterization facilities, leaving NASA the primary responsibility in this area.

OPTICAL DAMAGE PROBLEMS EXPERIENCED BY NASA

Optical damage problems have already adversely impacted two laser remote sensing programs currently under development by NASA, causing one program to switch to an entirely different laser. This, in turn, has led to schedule delays and cost growth. The problems encountered in each of these programs are briefly described below.

Lidar Atmospheric Sensing Experiment (LASE)

The goal of the LASE program is to measure water vapor concentration for atmospheric chemistry studies, using a laser mounted in a high flying aircraft, the ER-2. Problems with damage to numerous optical surfaces led the LASE program to drop alexandrite ($\text{Cr:BeAl}_2\text{O}_4$) as the laser of choice and to switch to titanium sapphire ($\text{Ti:Al}_2\text{O}_3$). The LASE program was originally scheduled for flights on ER-2 in 1988. However, the schedule slipped 6 years because of failures experienced with virtually every optical component during the development and testing of the alexandrite laser.

Because of its relatively low stimulated emission cross section, the alexandrite laser operates at higher saturation intensities. Running the laser efficiently, i.e., in the saturation mode, demands the optics to withstand the higher saturation fluences. At the designed energy levels, every optical component in the laser resonator suffered damage at some point in the program. After considerable effort was expended over several years to tame this laser, the continuing problems encountered with optical damage prompted a switch to a $\text{Ti:Al}_2\text{O}_3$ laser. The $\text{Ti:Al}_2\text{O}_3$ laser has a much larger stimulated emission cross section enabling it to operate efficiently at substantially lower energy densities. Operation at the lower energy densities allows more reliable operation while minimizing the optical damage threat. However, the $\text{Ti:Al}_2\text{O}_3$ laser still requires additional development efforts to further reduce laser damage occurrences.

Lidar In-Space Technology Experiment (LITE)

The goal of the LITE program is to measure aerosol concentrations and planetary boundary layer chemistry. These measurements are carried out using the harmonics of a Nd:YAG laser. During testing, LITE suffered damage to the frequency converter oven windows. After an intense effort involving careful oven redesign, the problem was solved by reducing the fundamental beam intensity. However, the intensities at the required harmonics are now much reduced as well.

SYNOPSIS OF THE PROPOSED NASA PROGRAM

During the workshop, three presentations were delivered by Langley Research Center and Goddard Space Flight Center (GSFC) personnel outlining the proposed NASA program. Plans for testing and certification of optics at different wavelengths and pulselengths were described, and the various aspects of interacting with optics manufacturers were discussed.

The main program elements were presented as follows:

- ▶ Database collection of available data
- ▶ Establishment of component test capabilities for NASA requirements
- ▶ Development of component test and certification standards
- ▶ Performance of component testing and certification
- ▶ Transfer of test results to manufacturers and the laser community

Database Collection of Available Data

Initial efforts of the NASA program plan focus on the collection and dissemination of existing damage threshold data on optical materials of interest to NASA's missions. Although many of the existing data on materials are dated or inappropriate due to the test parameters, these data are useful in the areas of test methodology, damage mechanisms, and correlation of damage data with analytical techniques. The primary sources for damage threshold data include the proceedings of the annual Boulder Damage Symposium (1969-present), MLO's damage database at 1.06 μm , and the Lawrence Livermore National Laboratory database covering wavelengths from the infrared (IR) to the ultraviolet (UV). In addition, information concerning damage of optical materials related to exposure to the space environment will be collected, including data from the Long Duration Exposure Facility (LDEF).

Establishment of Test Capability for NASA Requirements

Secondly, the program plan calls for the establishment of a test capability at NASA-unique laser wavelengths and pulselengths. Laser sources proposed for use in this capability include Nd:YAG, Ti:sapphire, Ho:Tm:YLF, and optical parametric oscillators for the mid-IR region. A picosecond pulse Nd:YAG system was also discussed. No direct duplication of existing commercial test facilities is envisioned. For example, for comprehensive testing at 1064 nm (ns pulse), NASA plans to utilize already established commercial test facilities. However, some initial testing will be performed at 1064 nm for correlation with the large database of information available. This Nd:YAG laser would then be used to pump a Ti:sapphire laser for future testing. A standard damage test set up was presented, allowing for future modifications for simulation of the space operational environment during testing.

Development of Test and Certification Standards

Once the necessary test capabilities are established, NASA proposes to develop standards for testing and certification of space laser optics. These standards will include specifications for damage threshold determinations, acceptance testing procedures for received optical components, qualification of optical components for spaceflight, and procedures for predicting the lifetime of optical materials. Whereas the first of these standards (i.e., the performance of damage threshold measurements) is well understood and accepted by the laser community, the remaining three are significant primarily to NASA, and therefore it is NASA's responsibility to not only develop these standards but also to ensure their application.

Performance of Component Testing and Certification

Having developed the necessary test capabilities and protocols, NASA will perform testing and certification of such components as laser rods, polarizers, mirrors, beam splitters, and windows. In accordance with mission priorities, NASA plans to sequence its testing as follows:

1064 nm/20 ns	Correlation with existing facilities
820 nm/20 ns	Program supported: LASE
1064 nm/75 ps	Program supported: Geodynamics Laser Ranging System (GLRS)
2.1 μ m/600 ns	Program supported: Coherent Laser Airborne Shear Sensor(CLASS) Laser Atmospheric Wind Sounder (LAWS)
mid-IR	Purpose: developmental laser programs

In order to enhance the damage threshold of optical components for NASA missions, the NASA plan proposes to collaborate with optics manufacturers to improve process controls. The successive-iterative process will be used to test a series of optics received from a single vendor. For each optical component, a vendor will produce the component, document the procedures, and send the optic to NASA for damage threshold testing. The threshold will be determined, the vendor contacted, and the optic refabricated using an improved procedure. Previous attempts using this process have produced improvements by a factor of 2 in the damage threshold of the optical

elements after a series of five iterations. The end result of this effort will then be twofold: (1) the damage threshold of the optical elements will be optimized for use in specifying component performance, and (2) a list of qualified suppliers will be generated for those components of interest to NASA, improving the procurement procedure.

Transfer of Test Results to Manufacturers and the Laser Community

NASA proposes to transfer the results of this program to the relevant NASA flight programs, the laser community, and to optics manufacturers. One mechanism discussed for this technology transfer is the existing Laser Materials Database that was developed at LaRC and is available upon request. Incorporation of damage threshold data, lists of qualified optical suppliers, and results of lifetime studies can be directly incorporated into this document. Additionally, the development of a NASA Space Laser Optics Handbook has been proposed to assist system designers in optics selection and purchase.

PANEL CHARGE AND EVALUATION

Dr. Frank Allario, Director for Electronics at LaRC, presented the charge to the panel consisting of an introductory statement and a series of questions. The introductory statement is given here, followed by the questions and their responses.

Introductory Statement

NASA is currently developing several laser systems for Earth and planetary observations that are critical to its science mission. To reduce the weight and power of such systems required for spaceflight, more efficient lasers must be developed. This increase in efficiency typically comes at the expense of high fluence levels and the increased possibility of optics damage.

During the discussion of the workshop's first day, you will be given an overview of NASA's remote sensing missions involving laser systems, problems encountered with laser-induced optical damage to date, and a proposed plan to improve the long-term reliability of such laser systems for future spaceflight. The following questions are suggested as a guide to focus your attention on the assessment of NASA's need for such a program and the viability of the proposed program itself.

Panel Evaluation

Program Justification

NASA currently has no coordinated effort to resolve laser damage issues for flight systems.

Should NASA continue to resolve these issues and/or problems on an experiment-specific basis, or should it develop a generic quality assurance program to improve the reliability of laser-system optics for spaceflight?

The panel was unanimous in its conclusion that NASA must address reliable spaceflight optical systems through a comprehensive optics reliability program having top priority. The panel also strongly advised that NASA allocate an adequate budget for space-optics reliability improvements, using the proposed program as the agency's source of laser-induced damage information (e.g., protocols, vendor performance information, coating design). Trying to achieve ultra-high reliability on only a program-by-program basis would be wasteful both in terms of money and intellectual energy. All of the planned laser-sensor spaceflight systems share common technology issues, and it would be only prudent to have them addressed collectively in one program. However, a strong interaction with NASA flight programs was encouraged to ensure applicability of the testing parameters.

Are the laser-induced optics damage issues sufficiently defined to establish a Code QE program?

The panel finds laser-induced damage issues to be quite well defined, but it is important to recognize that they extend beyond the program area of responsibility of Code QE. First, the most important issue to be addressed is how to test laser and/or optical systems for reliable operation for 10^9 pulses. Can NASA develop certification techniques which will ensure reliability over that many pulses (10^9 pulses requires 3.2 years of elapsed time at 10 pulses per second)? What is the probability of a certified part failing? Does one know how to assign statistically significant reliability numbers to these optical components? Furthermore, do laboratory-certified parts remain robust in the platform and space environment? A mission

quality and standards organization could spearhead action on these issues, perhaps with assistance from other organizations having responsibility in optics and laser technology.

Technical Standards, Status, and Development

NASA has experienced problems in obtaining reliable high-threshold optics for aircraft and space-flight experiments.

Are there technical, manufacturing, performance, or testing standards and/or specifications by, say, DOD, the American National Standards Institute, or industry that can be adopted by NASA to ensure procurement of reliable optics?

In general, the panel finds a dearth of standards for ground-based systems. For meeting space needs, there is a void that NASA needs to fill. Some of the existing ground specifications, however, should assist in the preparation of suitable specifications for space use. The list of documents below is considered crucial to the program in the definition of space hardware specifications.

"Laser Damage Certification of Designator Optical Components," June 29, 1990, Missile Interim Specification (MIS) 36477, USA MICOM, Huntsville, AL.

"Test Method for Laser-Radiation-Induced Damage Threshold of Optical Surfaces," April 24, 1991, Draft International Standard (CD 11254), Document number ISO/TC172/SC9/WG-6.

"Cleaning Laser Systems Hardware," March 7, 1988, Missile Interim Specification (MIS) 23542, MICOM, Huntsville, AL.

"Standard for the Preparation of Drawings for Optical Elements in Systems," Draft International Standard (CD 10110), Document number ISO/TC172/SC1/WG2.

"Handbook of Optical Standards," Robert Parks, (Ed.), Optical Society of America Handbook, in preparation for 1993 publication

If not available, would the development of such standards and/or specifications improve the reliability of spaceflight optics?

Reliability would certainly be enhanced by establishing more test specifications and standards, but before standards can be written, NASA must first develop an approach or approaches to accelerated life testing and life prediction. There are various materials characteristics for which test standards could and should be developed (surface characterization, subsurface-finish characterization, inclusion mapping), but doing so is secondary at this time to developing the standards and specifications for accelerated component life testing and life prediction. No one else will undertake that effort for NASA without NASA encouragement. NASA may also develop guidelines for process control documentation by vendors, which may be important in assuring reproducibility.

Can such standards be established?

Standards can be established for materials characteristics and for process controls. The latter will result from "build-test-build-test" measurement activities in concert with optics manufacturers. Assuming that accelerated life testing and prediction can be achieved, standards covering these parameters can be established as well.

Damage Threshold Testing

Lasers operate within specifications, provided the damage threshold of the optical components is known and the system stays within acceptable damage levels.

Assuming damage threshold testing is helpful in establishing the reliability of optics, what measurements and/or data are available?

There are numerous sources of damage-threshold measurement data that have been accumulated by various facilities, and these are helpful in getting the NASA program started in this area. As a first resource, data from over 20 years of laser damage knowledge are documented in the proceedings of the Boulder Laser Damage Symposium. The proceedings report on measurements, bulk-damage mechanisms, optical fabrication techniques, and damage measurement procedures. In addition, MLO has published an extensive database covering a wide variety of optical materials and components tested at important wavelengths, various pulse durations, and pulse repetition frequencies. The Lawrence Livermore National Laboratory maintains a growing database covering wavelengths from the IR to the UV. Other potential sources of information are (1) DOD Laboratories such as the Naval Weapons Center, Naval Research Laboratory, Air Force Phillips Laboratory (formerly Air Force Weapons Laboratory), Air Force Wright Laboratories (MLPJ); (2) universities such as the University of Central Florida, University of Southern California, and University of Rochester; and (3) private sector laboratories such as Lockheed, Hughes, Rockwell, Litton Itek, and Battelle NW. Information on system- and environment-related damage on military reconnaissance satellite laser communication up-, down- and cross-links may be available from respective DOD commands. However, virtually no information is available on lifetime determinations for optical materials.

Can these existing optical damage-threshold measurements and/or data be extrapolated to cover the laser wavelengths, repetition rates, etc. of interest to NASA's future?

No. Existing optical damage-threshold data can provide only an approximation of what to expect when components are used at other wavelengths, pulse durations, and pulse repetition frequencies. In general, the only way to assure adequate understanding of damage thresholds is by testing components from a specific supplier under conditions that duplicate the flight operations environment. Without actually testing a component in the flight system, comparisons between the flight operational regime and the test conditions will be needed for beam spot size, lifetime, thermal loading, and all extrinsic factors introduced by the platform or the environment.

A good example of environmental impact on laser operation is the LITE program where a critical, triple antireflective coating, which had worked flawlessly under *normal laboratory conditions* for 2 years, suffered coating etching in *dry nitrogen*, leading to a 10% loss in transmission within a few hours of testing. This incident's lesson is that future relevant testing requires the best estimate of mission environment and duration for each future flight program to be compiled and measurements to be conducted in an environment closely resembling that of the actual flight.

Should NASA establish an in-house laser-damage threshold test capability to determine standards for NASA spaceflight components?

The panel finds that a two-pronged strategy will yield greatest benefits to NASA with the least recurring costs and at the fastest rate. First, already established commercial or university-based facilities can be relied upon to deliver damage-threshold results at specific wavelengths and pulselengths, obtained with conventional data analysis methods. Second, NASA needs to plan promptly for and then establish (in a phased manner) laser-damage test facilities around laser sources that are unique to current and future NASA needs. Ti:sapphire and the 2- μ m laser source belong in this category. Both test sources require major, nonrecurring capital equipment outlays.

Recognition that establishing the damage-test facilities solves only part of the problem is critical. If the samples to be tested are inadequately characterized, it will not be obvious how to interpret the results obtained from those samples. Sample characterization, whether carried out by a NASA facility or by the sample supplier, needs to be carried out with the same insistence on comprehensiveness and precision that is the guiding principle for damage testing.

NASA Program Plan

LaRC has, with input from other NASA field centers, developed a program for establishing technical standards, measurement methods, and measurement facilities, aimed at improving the reliability of lasers in space and aeronautical flight systems.

Is this program likely to produce the desired results?

At present, there is not a single panel member who can attest that current optics will, with certainty, live up to NASA's stringent lifetime requirements (e.g., 10^9 pulses) because of the lack of experimental data at these conditions. Therefore, the first priority of the NASA program should be to determine the estimated lifetime of optics manufactured today. At this point, the decision will be made as to whether improvements in optic quality are necessary. It is at this point that a more careful investigation of improvement techniques will be warranted.

Damage threshold improvement programs for certain types of coatings are typically considered successful if improvements by a factor of 2 to 5 are achieved. Rarely, if ever, is a full order of magnitude improvement realized in a single technology path. Suppose, for example, the best available optic is able to survive only 10^7 pulses. A spectacular improvement in the conventional sense would be a survival enhancement of 10^8 pulses, still a whole order of magnitude short of what the flight programs mandate. Therefore, the NASA program must guard against the assumption that, within the allotted program time, reliable, damage-free components will be found for each mission. It would be a more realistic goal to determine which optics cannot be improved to desirable levels and address system redesign to reduce the threat of

damage to these elements. Addressing damage tolerance in this manner is a realistic result of this program, leading to enhanced reliability.

In what way could this program be improved?

The LaRC program plan focuses on developing a damage testing capability, developing component test, qualification and certification protocols, performing component testing, and transferring technology-improvement results to NASA flight programs. In the panel's view, the plan could be improved in several areas.

- The highest priority should be given to developing an approach to accelerated component life testing and life-prediction techniques which will ascertain that components developed as a result of this program will perform reliably over 10^9 pulses.
- Testing for platform and environmental effects needs to be clearly defined and a logically compelling, experimental course of action needs to be devised. A realistic approach to this was not addressed in detail.
- The plan places an almost naive trust in the optical supplier (i.e., vendor). The plan relinquishes any will by NASA to control materials issues and withdraws into the narrow responsibility of damage-threshold measurements. If NASA has decided not to have a part in materials selection, manufacturing, and coating-design activities, at the very least NASA should aspire to a leading presence in sample characterization and certification.
- For several missions the technology freezing dates are so close that the program can impact mission-laser engineering only if prime contractors are brought into the program to work with Langley immediately on improving component reliability. Details for this were not addressed.

Is the effort and schedule proposed reasonable?

The panel did not receive a formal presentation on budget and schedule proposals. Various funding and scheduling options were discussed informally. Panel members with experience in government laser-systems programs reported that a funding figure of 2-5% of total laser-system cost, earmarked for optical materials improvement activities, is a useful figure for NASA to consider. In comparison, a figure of \$500,000 per year, considered realistic by NASA at this time, was deemed sub-bare-bones even if no new laboratory infrastructure were to be built in support of the

program. Recurring annual costs for damage-test facility upkeep, sample acquisition, and database management will total at least \$500,000, excluding the cost of government personnel salaries.

Should NASA proceed with the development of the program?

The need for this program is quite clear. The panel urges NASA to commence with the program at the earliest time possible and to seek adequate funding for its success.

How Industry Participation Can Be Optimized

Program success of the current NASA program plan depends on a high level of vendor and/or supplier participation and response.

Can the optics industry be expected to cooperate in the development of optics manufacturing, performance, and/or testing standards?

The answer to this question will depend upon the amount of business expected in the area. Because of the limited number of optical components on each flight-sensor platform, the incentive for industry participation appears minor. In two specific areas, however, this does not hold: (1) testing for qualification and certification at already available wavelengths at a commercial testing site; and (2) coating development, if the coatings were for a widely used wavelength (Nd-fundamental or one of its harmonics) where benefits reaped from the few-component NASA program can be easily transferred to the mass market.

What information on (proprietary) manufacturing processes can be expected from vendors?

NASA should expect none unless NASA opts for a captive contractor with adequate substrate preparation, polishing, cleaning, coating, and sample characterization capabilities. Many vendors will feel reluctant to divulge proprietary information other than what is readily attainable or measurable from their delivered products. This will include subtleties in operating procedures and process control of which the vendor may not have satisfactory knowledge. Vendors may also feel reluctant to be

associated with such tests for fear of being publicly ranked low relative to their competitors. The panel considers a captive contractor a valuable program option for NASA.

Is it reasonable to expect the successive-iterative process to yield enhanced optics damage thresholds and manufacturing and reliability standards for spaceflight?

Historically, the iterative approach has been the principal method used successfully by DOD, DOE, and private industry to develop enhanced damage-resistant optics. A reasonable expectation is that this approach will enhance damage thresholds for NASA as well. To assure that it will, NASA must emphatically insist on strict vendor process control protocols and utilize comprehensive sample characterization means. Once the protocols for manufacturing and testing are in place, formulation of standards for space optics will become a reality. However, NASA must be aware that some level of improvement will be lost over the years if the volume driving the development of a particular coating or design is relatively low. Therefore, NASA must place its first priority on defining damage thresholds and lifetime durabilities and have the improvement of these as a secondary goal.

PANEL RECOMMENDATIONS

After responding to the specific questions included in the charge to the panel, the panel was asked to put forth a set of recommendations for NASA regarding its needs in the area of optics damage. These recommendations, listed below, address the viability of a NASA laser damage program, its necessary scope, and extrinsic issues which must be solved for NASA to ensure reliable laser optics for its space-based systems.

1. NASA must implement a program to address laser-induced damage issues relevant to its laser remote sensing missions. The uniqueness of NASA's laser system requirements, particularly the long lifetimes in space, demand that NASA address system reliability.
2. The proposed program should commence in FY 1992 in order to produce initial results by 1995 for timely incorporation into flight programs.

3. Support of a detailed program plan commensurate with the scale of improvements necessary to ensure laser system reliability should be allocated approximately 2-5% of NASA's total laser development budget. The budget presented to the panel of \$500,000 per year will force a narrower scope to the NASA program, limiting the improvements that could be made. The panel also fears that the development of some testing methodologies may demand resources out of line with such cost limits.
4. Because of the funding limitations, the success and value to NASA of this program will be directly proportional to the degree of teaming with industry; the sharing of resources, information, and expertise, and the level of cooperation with the flight programs. Cooperation with outside sources will prevent unnecessary duplication and ineffectiveness. Periodically convening an external advisory group is also desirable for keeping the program in line with current technology and for assuring objective evaluations.
5. Specifications for processing, handling, and testing of space laser optics are currently absent. Future NASA missions will depend on such specifications to ensure reliable space systems. NASA should, therefore, focus its efforts on the development of such specifications and the application of these in-flight systems. One possible mechanism for ensuring appropriate use of standards developed in this area is to compile a NASA Handbook of Specifications for Lasers, covering fault-tolerant design, space-platform compatibility, preferred materials, preferred processing techniques, and testing, acceptance, and qualification protocols.
6. Special emphasis must be placed on establishing test systems that meet NASA's unique requirements, such as accelerated long-term optics durability testing. Test methodologies including advanced statistical experimental design techniques must be developed for meaningful accelerated lifetime data analysis.
7. A successive-iterative optics improvement approach, starting with a close working relationship between the optics manufacturer and the damage tester, will yield best results if NASA maintains full sample characterization control. NASA must remain

realistic about the quantity of processing information that the vendor will be willing to provide. Use of comprehensive characterization techniques will provide NASA with necessary information to better interpret results.

8. Extrinsic damage issues must be properly addressed by NASA to ensure overall reliability of laser systems, although these issues may be outside the scope of this program due to funding limitations. Efforts, external to this effort, should be pursued, with emphasis on the funding of basic university research in optical materials processing and laser-material interactions.

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